Nearshore Sediment Transport Modeling: Collaborative Studies with the U.S. Naval Research Laboratory

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LONG-TERM GOALS

The goals of this work are to obtain better understanding of sediment mobilization, transport, and deposition across the wave bottom-boundary layers (WBBL) in the surf and swash zones and to improve predictive capabilities for bed load and suspended sediment transport as a function of environmental parameters, including wave heights, breaker characteristics, sediment properties, beach slope, bottom roughness, local water depth, wave frequency spectra, and the presence of low frequency circulations such as along shore currents and undertow.

OBJECTIVES

We are presently focused on addressing two key aspects of sediment transport:

1.) to simulate coupled two-phase flow, particularly for bed-load dominated flow regimes, utilizing three-dimensional hydrodynamic direct numerical simulations of the turbulent, wave bottom boundary layer and discrete particle modeling.

2.) to assess the strengths and weaknesses of the individual model capabilities and address deficiencies as guided by the lab and field data.

APPROACH

The work involves theoretical and model development, numerical computations, and comparison with laboratory data. The primary experimental tools are three-dimensional discrete particle and direct numerical simulation hydrodynamics models of oscillatory, turbulent boundary layers.

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14. ABSTRACT **The goals of this work are to obtain better understanding of sediment mobilization, transport, and deposition across the wave bottom-boundary layers (WBBL) in the surf and swash zones and to improve predictive capabilities for bed load and suspended sediment transport as a function of environmental parameters, including wave heights, breaker characteristics, sediment properties, beach slope, bottom roughness, local water depth, wave frequency spectra, and the presence of low frequency circulations such as along shore currents and undertow.**			
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WORK COMPLETED

The model being developed here will challenge and refine existing parameterizations for bedload and suspended load transport rates. Fundamental concepts used in describing the phenomena of sediment transport such as the reference concentration, bed failure criterion, and the more recently introduced concept of acceleration-induced transport will be more accessible for study with the new model. It will produce the high level of detail necessary to refine our present understanding of sediment transport processes and clarify new directions in the measuring techniques needed to improve present predictive capabilities.

Our approach integrates the turbulent boundary layer hydrodynamics model of Moneris and Slinn (2004) (Figure 1) with the discrete particle model of Drake and Calantoni (2001) (Figure 2). The models are being integrated with two-way coupling between the fluid and solid phases. The hydrodynamic model uses control-volumes slightly larger than individual grain sizes. The fluid model passes the three instantaneous Cartesian components of momentum in a turbulent boundary layer under oscillatory free-stream flows to the particle locations. The momentum exchange (updated approximately 1000 times per second) is calculated using an empirical drag coefficient. Global momentum is conserved, and as a particle accelerates the local fluid velocity decreases, or as the particle decelerates, the local fluid velocity increases. It is not perfect, but it is, arguably, a rational step towards increased realism in both the hydrodynamic and discrete particle modeling approaches.

There are several initial complexities with coupling the models that we are addressing in the development stages. First is matching the spatial scales of the two models. To produce a reasonable turbulence field the hydrodynamics model needs to include at least 5-10 horizontal eddies in each direction of the periodic domain. Typical small eddy diameters, in simulations over smooth boundaries and sand ripples (Barr, Slinn, Pierro, Winters, 2004) are around 0.5 cm to 1 cm. Therefore, we desired to have a model domain on the order of 2-10 cm to allow the hydrodynamics to be free to develop in a more natural manner. We settled on a 4 cm horizontal length scale for the domain. To accommodate this hydrodynamic constraint, the particle model was optimized to allow more particles in the domain. We can simulate approximately 100,000 particles for 10-20 seconds of simulation time in about a day or two of CPU time. The second complicating issue is that as the particles move across the domain they reside in multiple fluid control volumes and we need to know the mass of each particle in each control volume to a high degree of accuracy. In order to appropriately attribute the exchange of momentum between the fluid and particulate phases, we needed to know the portions of each particle in each fluid control volume as a function of time. This important detail has been worked out for a particle crossing through a corner (as illustrated in Figure 3 below) it can occupy portions of up to 8 control volumes simultaneously.

There is an additional complexity. There is a new level of sophistication required in the model because the fluid does not occupy all of the space. This greatly complicates the mathematical method required for solution of the fluid pressure field. For a uniform density flow field, the coefficients that appears in front of the Poisson's equation for pressure are constant (the density). However, for the variable density field (arising from portions of the control volume being filled with sand particles), the coefficients are spatially and temporally variable. They can be calculated, by integrating forward the particle positions, but the computationally efficient direct pressure solution method that worked in the old fluid model must be replaced with a slower multi-grid pressure solver (as used by Barr, Slinn, Pierro, and Winters, 2004) or an iterative technique (as used by Slinn, Allen, Holman, 2000). Iterative techniques introduce new mathematical uncertainty to the model solution, because they require convergence criteria and tolerance levels. This aspect of the problem is the main technical challenge remaining. We are seeking to obtain an efficient, stable algorithm. Details of the total model algorithm are given below.

RESULTS

The model equations to be solved for the two-phase flow are presented (e.g., Dong and Zhang, 1999; Hsu et al., 2004). The modified momentum equation is

$$\rho\left[\frac{d(\varepsilon\vec{u})}{dt}+(\vec{u}\bullet\nabla)\varepsilon\vec{u}\right]=-\varepsilon\nabla p+\mu\nabla^2(\varepsilon\vec{u})+\rho\varepsilon\vec{g}-\vec{f}_{reaction}+\varepsilon F_{Applied}\,, \qquad (1)$$

and the modified continuity equation is $\frac{d\varepsilon}{dt}+\nabla\bullet(\varepsilon\vec{u})=0$, (2)
where $\varepsilon=1-c$ is the local porosity of the fluid, c is the particle concentration at the grid volume, ρ is the fluid density, $\vec{u}$ is the fluid velocity, p is the pressure, μ is the dynamic fluid viscosity, $\vec{g}$ is the acceleration due to gravity, and $\vec{f}_{reaction}$ represents the coupling force which is the component of the particle drag force acting back on the fluid volume and $F_{Applied}$ is an applied external pressure gradient that drives the wave bottom boundary layer flow. The pressure field is determined iteratively because of the non-constant coefficient ε^{n+1} in front of ∇p^{n+1} at the new (n+1) time level in the 3rd order Adams-Bashforth time stepping scheme using the projection method. It is convenient to divide through by ε^{n+1} and then take the divergence of the momentum equations and add them to obtain.

$$\nabla^2 p^{n+1}=\frac{\rho}{\Delta t}\left\{\frac{\nabla\cdot(\varepsilon\vec{u})^*}{\varepsilon^{n+1}}-\frac{1}{\varepsilon^{n+1}}\nabla\cdot(\varepsilon\vec{u})^{n+1}-\frac{\partial}{\partial x}\left(\frac{1}{\varepsilon^{n+1}}\right)(\varepsilon u)^{n+1}-\frac{\partial}{\partial y}\left(\frac{1}{\varepsilon^{n+1}}\right)(\varepsilon v)^{n+1}-\frac{\partial}{\partial z}\left(\frac{1}{\varepsilon^{n+1}}\right)(\varepsilon w)^{n+1}\right\}$$

The continuity equation applied at the $n+1$ time level $-\frac{\partial\varepsilon}{\partial t}=\nabla\cdot\varepsilon\vec{u}$ is used to replace the second term on the R.H.S. The last 3 terms are unknown since u^{n+1}, v^{n+1}, w^{n+1} are still unknown until the iteration has converged. So $\nabla^2 p$ can be solved with iterative approximations to these. Finally:

$$\nabla^2 p=\frac{\rho}{\Delta t}\left\{\frac{\nabla\cdot(\varepsilon\vec{u})^*}{\varepsilon^{n+1}}+\frac{\partial\varepsilon}{\partial t}-\frac{\partial}{\partial x}\left(\frac{1}{\varepsilon^{n+1}}\right)(\varepsilon u)^{n+1}-\frac{\partial}{\partial y}\left(\frac{1}{\varepsilon^{n+1}}\right)(\varepsilon v)^{n+1}-\frac{\partial}{\partial z}\left(\frac{1}{\varepsilon^{n+1}}\right)(\varepsilon w)^{n+1}\right\}$$

Note that $\nabla\cdot\left(\frac{1}{\varepsilon^{n+1}}\right)\approx 0$ in both clear water $(\varepsilon=1)$ and the packed bed $(\varepsilon\approx 0.3)$ zones, and these unknown terms may converge rapidly except across the fluid-particle interface.

We set convergence criteria in a standard fashion, $\int_v \sum \left(u_i^{n+1,m} - u_i^{n+1,m-1}\right) \leq \gamma$. For Boundary Conditions at the top and bottom $\left.\frac{\partial p^{n+1}}{\partial z}\right|_B = \frac{-\rho}{\Delta t \varepsilon^{n+1}}\left[\left(\varepsilon w\right)_B^{n+1} - \left(\varepsilon w\right)_B^*\right]$ and we want boundary conditions $w_B^{n+1} = 0$, so $\left.\frac{\partial p^{n+1}}{\partial z}\right|_B = \frac{\rho}{\Delta t \varepsilon^{n+1}}\left(\varepsilon w\right)_B^*$. The governing equation for the motion of a spherical particle is given by (e.g. Madsen, 1991)

$$\rho_s V_s \frac{d\vec{u}_s}{dt} = \left(\rho_s - \rho\right)V_s\vec{g} + \frac{1}{2}\rho C_d' A\left|\vec{u} - \vec{u}_s\right|\left(\vec{u} - \vec{u}_s\right) + \rho V_s \left.\frac{D\vec{u}}{Dt}\right|_{z=\infty} + \vec{F}_\phi, \quad (3)$$

where ρ_s is the sediment density, V_s is the particle volume, $\vec{u}_s$ is the particle velocity, C_d' is the modified drag coefficient, A is the projected area of the sphere and $\vec{F}_\phi$ is the sum of inter-particle forces. The first term on the right hand side of the equation represents the particle buoyancy. The second term represents the particle drag force where the drag coefficient is calculated from a fit to the empirical drag law for a sphere, $C_d' = c^*(24Re_s^{-1} + 4Re_s^{-\frac{1}{2}} + 0.4)$, where c^* represents a modification based on the local particle concentration (e.g. Richardson and Zaki, 1954), $c^* = (1 - c - \frac{1}{3}c^2)^{-\frac{5}{2}}$. The third term represents the applied horizontal pressure force, which is the driving force of fluid and particle motion in the model, written here in terms of the free stream fluid acceleration. A number of fluid-particle interaction forces (e.g. added-mass, Bassett history, Magnus forces) have been ignored with this initial formulation. Consider the reaction term, $\vec{f}_{reaction}$, in (1) is the equal and opposite force to the particle drag force. The reaction term has dimensions of force per unit volume in (1). The particle drag found in (3) has dimensions of force. In general, the reaction term in (1) may be written as $f_{reaction} = \frac{1}{2}\frac{1}{V_s}\rho C_d' A\left|\vec{u} - \vec{u}_s\right|\left(\vec{u} - \vec{u}_s\right)$. The particle drag force is assumed to be a body force acting through the center of mass of the particle. The fluid velocity, $\vec{u}$, found in (1) is the estimated velocity at the center of the sphere. When the fluid velocity is constant over a large volume compared to the particle then the estimate is trivial; the velocity of the fluid at the center of the particle is estimated to equal the velocity of the fluid volume where the center of the particle is located. However, for our problem a sediment particle could span many grid volumes (of fluid) in the vertical, while at most four volumes in the horizontal, the task of estimating the particle drag force using the empirical drag law for a sphere while simultaneously satisfying Newton's Third Law becomes problematic. Due to the stretched vertical grid a sediment particle may occupy volume in over 20 different fluid grid points simultaneously. Determining a reasonable estimate of the fluid velocity at the particle's center for use in the empirical drag law is no longer trivial. There is NO clear choice that seems obviously better than the other possibilities. Some methods will be more computationally efficient than others, but one could argue that their use sacrifices accuracy and more importantly, fidelity to the physics.

After careful consideration, we have chosen a method for computing the velocity at the center of a particle for our baseline simulations that is somewhere in between the extremely difficult and trivial. In practice, there are at least two necessary constraints that need to be satisfied when determining how to compute the reaction term. The concentration of particles in fluid grid volumes must always be less than unity. More realistically the concentration should not be allowed to exceed about 0.7. As a result of this constraint, there will be some trade off between the scale of the turbulence resolved and the largest particle allowed in the simulation. For baseline simulations the horizontal grid spacing will be uniform in both the $\hat{\mathbf{i}}$ and $\hat{\mathbf{j}}$ directions. The length of the side of the horizontal square bounding a fluid grid volume needs to be greater than or equal to the diameter of the largest sediment particle. Simply written, the first constraint is $\varepsilon > 0$ true for all space and time in the simulation.

The second constraint is that Newton's Third Law must be strictly enforced! When a sediment particle is much smaller than the fluid grid volume the easiest method for obeying Newton's Third Law is clear. The fluid velocity used to compute the drag force is just the velocity of fluid at the grid point where the center of the particle resides. The computed drag force is generated entirely from a single grid point and is simply projected back onto that grid point with equal magnitude and opposite direction. For our configuration the particle may occupy volume in many grid points simultaneously and it is not possible to choose a single grid point for fluid-particle interactions without violating the first constraint. Implicitly assumed is that the total mass of fluid and particles will be conserved for all time and space in the simulations.

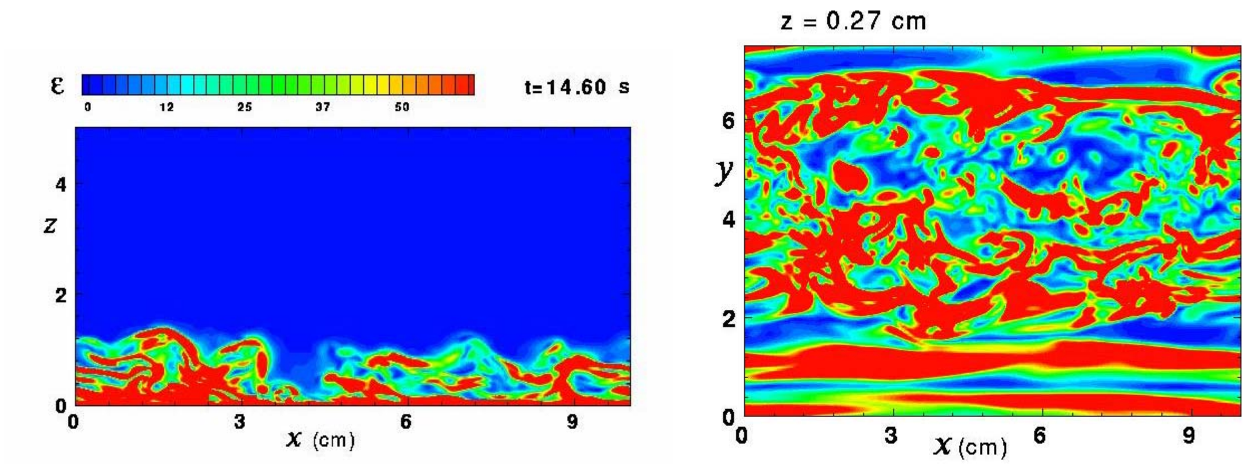

Figure 1. Turbulent kinetic energy dissipation rates in a simulation of a turbulent wave bottom boundary layer during a phase of flow reversal. The left panel shows a vertical plane, and the right panel shows a horizontal plane located 2.7 mm from the boundary during flow transition.

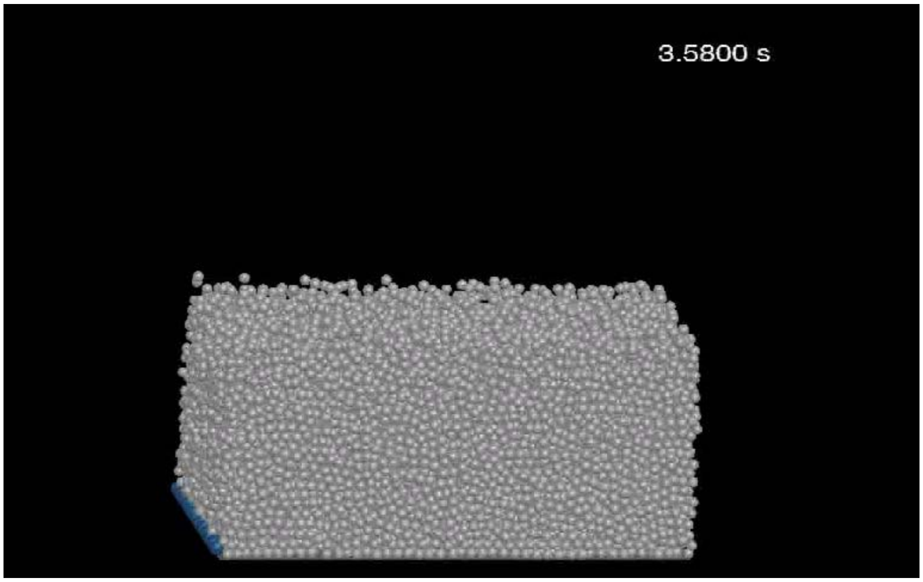

Figure 2. Discret particles during a simulation.

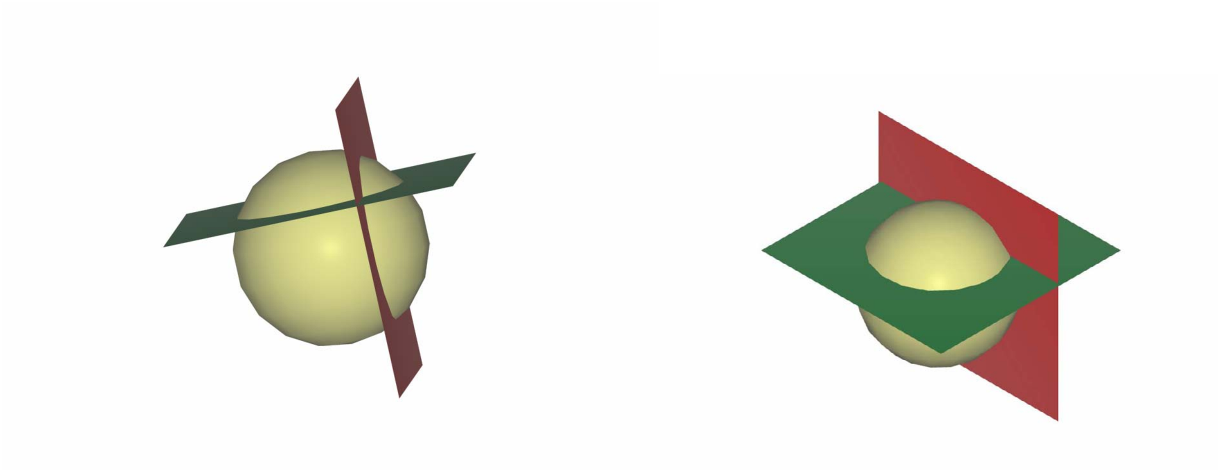

Figure 3. The position of particles crossing control surfaces must be accounted for precisely to accurately determine the mass of fluid and solid in each control volume. A complex algorithm has been developed to efficiently determine the location of the mass of each particle in motion.

IMPACT/APPLICATIONS

Our models are the most sophisticated, detailed models of turbulence and sediment transport ever implemented. This approach should allow much more detailed understanding of the complex physics of two-phase flows. The model results will permit evaluation of bulk transport formulas.

RELATED PROJECTS

Modeling projects for the Sand Ripple DRI are related.

PUBLICATIONS

None yet.

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